ECL-30

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RADIATION PRODUCTS COMPANY

Failure of a Rotating Mirror

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In August, 1964, Mr. Willard Buck, Consulting Engineer for Radiation Products Company was confronted with the problem of failures in the rotating mirror assemblies manufactured by the company for use in high speed photographic cameras. The mirror was rectangular, supported by ball bearings, and turbine-driven by compressed air or helium at 10,000 rps.[1] The failures occurred in the form of either a broken mirror shaft or a completely shattered mirror.

[1] rps - Abbreviation for revolutions per second.

Prepared in the Design Division of the Department of Mechanical Engineering by J. Kendall Williams under the direction of Dr. Henry O. Fuchs with financial support from the National Science Foundation.

Radiation Products Company

The rotating mirror assemblies were manufactured at Radiation Products' Turbine Department facilities in Santa Clara, California. The Turbine Department was organized in 1962. Its principal products were several types of rotating mirror assemblies for use in high-speed cameras and in laser devices. These assemblies were sold solely through Beckman and Whitley cameras. Radiation Products and Beckman and Whitley are both subsidiaries of another company, Technical Operations, Inc. Typical examples of the Turbine Department's products are described in greater detail in Exhibit 1. In 1964, employees of the company consisted of the Turbine Division manager, assistant manager, consulting engineer, mechanical engineer, secretary, draftsman, two testing laboratory technicians, and five machinists

Mr. Randy Sherman, Turbine Division Manager, supervised production, engineering, assembling, and testing operations involved in manufacturing rotating mirror assemblies. Mr. Dwight Smith, Assistant Manager, supervised and assisted in testing and assembly operations. Mr. Willard Buck, consulting engineer, assisted in the design of high-speed cameras and experimented with new uses for high-speed rotating mirrors. Mr. Bob Herbold, mechanical engineer, supervised production of present rotating mirror assemblies and designed and performed experiments on new rotating mirror devices. Mr. Derold Hansen, draftsman, designed detailed parts and made drawings for new rotating mirror assemblies. Resumes of professional activity of these employees are noted in Exhibit 2.

The company's facilities included a central office area; an optics laboratory equipped with optical benches and other optical equipment for testing cameras and lenses; a machine shop equipped with precision lathes and grinder; a drafting room; and an assembly and testing room where the mirror assemblies were assembled and tested prior to shipment. These facilities totaled 2,000 square feet.

High Speed Cameras

The mirror assemblies manufactured by Radiation Products were used in high speed cameras of either the "framing" or "sweeping image" types. Both types of cameras were used to photograph events whose duration was in the order of several micro-seconds, such as the propagation of shock and flame fronts from high explosives.

The framing camera is described in Exhibit 3, pages 1 through 4. The framing camera was primarily used for qualitative observations of high-speed events. Quantitative data from framing camera photographs was frequently obtained by including a two-dimension grid as background for the event. A timing device in the rotating mirror assembly was used to synchronize mirror position and detonation of the event.

The sweeping image camera was used primarily for quantitative photographic measurement techniques. Unlike the framing camera, light from the event passed through a narrow slit apeature in the objective lens assembly and was reflected by a rotating mirror to form a single image on a strip of photographic film concentrically located with respect to the mirror axis. The event image was swept across the film surface by rotation of the mirror. In the case of detonation of a stick of explosive, for example, propagation of the highly luminous shock wave front along the stick was recorded as a diagonal stripe. Distance along the stick was measured across the film as a width. Distance along the film length was converted to time using the known rotational speed of the mirror. The mirrors used in sweeping image cameras are different from the mirrors which gave the problems described here.

Los Alamos Laboratory Rotating Mirror Developments, 1949-1952

Development of turbine driven mirrors of the type used by Radiation Products began in the late 1930's under the direction of Professor J. W. Beams of the University of Virginia. Professor Beams successfully operated a turbine driven mirror at 4800 rps. In 1949, when the Los Alamos Scientific Laboratory began its investigations of high-speed photography under the auspices of the U.S. Atomic Energy Commission, engineers there turned to Professor Beams' work to begin the development of faster turbine driven mirrors.[1] Professor Beams sent his turbine assembly to Los Alamos in December, 1949.

Professor Beams' rotating mirror assembly consisted of a 3/4 inch by 1-1/4 inch rectangular steel mirror, supported at both ends by sleeve bearings. The bearings were lubricated by oil under pressure supplied from an external source. A turbine rotor was attached to the end of the bearing shaft by a flexible coupling outside the mirror bearing Driving air was supplied to the turbine at pressures and flow rates up to 50 psig, 50 cfm.

After initial experimentation with Professor Beams' mirror assembly, Mr. Willard Buck, a mechanical engineer for the Los Alamos Laboratory, believed there were several aspects of Professor Beams' design that needed

[1] Willard E. Buck, "High-Speed Turbine Driven Rotating Mirrors," The Review of Scientific Instruments, Vol. 25-2, 1954, pp. 115-119.

development. He said, "The turbine has to be rugged, reliable, and simple to operate. There should be no waste products such as oil inside the camera. The rotational speed of the mirror has to be as high as possible, because this determines the value of the camera. I think that there are three problems in designing a new rotating mirror assembly which should be attacked simultaneously. The first is to obtain steel of the highest strength possible; the second is to design a bearing and a turbine system which would hold the mirror in place and spin it to the desired speed; and the third is to eliminate oil spray." Mr. Buck noted that since the main difficulties with Los Alamos preliminary designs and Professor Beams' turbine were bearing failures, this problem was attacked first.

New bearings designs investigated were divided into three groups: (1) liquid lubricated designs similar to the one used by Professor Beams; (2) high speed precision ball bearings; and (3) externally pressurized air bearings. Experiments were conducted simultaneously on these three types of bearings.

Two engineers had been working at Los Alamos since 1947 on ball bearing mounted mirrors and had reliably operated a 3/4 inch by 1-1/4 inch rotating mirror at 2500 rps. Operation at higher speed, however, resulted in bearing failures in the form of galled bearing races or bearing overheating which destroyed the fiber ball cage. Variations on the shaft-mounted bearing design were tried including smaller diameter bearings to reduce ball speed and rubber or plastic mounted bearings to absorb vibrations. The performance of 2500 rps was never improved, and experimentation with other types of bearings was continued.

Several types of air lubricated bearings were tried by Los Alamos engineers in attempts to eliminate oil mist and bearing overheating problems which had occurred earlier in Professor Beams' mirror assembly. Air bearings were either of the pressurized or non-pressurized type. Both types functioned and performed identically with the exception of the way the mirror shaft was supported at low speeds. In the pressurized air bearings, the shaft was supported by a "film" of air at all speeds. In the non-pressurized air bearing, the shaft was supported by a direct contact with the bore at low speeds. This contact required use of materials like teflon for bore liners. The mirror shaft became air supported at speeds high enough to induce laminar flow of air contained in the bearing clearance area. The air bearing typically consisted of a 1/4 inch diameter shaft which turned inside a cylindrical bearing bore. Clearance between the shaft and bore was approximately 0.0001 inches. Reliable operation of both types of air bearings was obtained at speeds up to 3000 rps. Mr. Buck said, "At higher speeds, metal to metal contact occurred between the shaft and bearing. This contact usually resulted in destruction of the bearing surface and required replacement of the bearing. Experiments with the air bearing were discontinued in favor of further development of the liquid lubricated sleeve bearings. It is still not clear why air bearings could not be made to work satisfactorily at higher speeds."

Mr. Buck noted that the design of the liquid lubricated sleeve bearings was carried out at the Laboratory by following the recommendations given in Analysis and Lubrication of Bearings[1] by Shaw and Macks. This book gives suggestions on bearing material, proper lubricant, cooling effects, and other less widely know characteristics such as bearing oil film whirl. Silver was chosen for the bearing material because of its high heat conducting capacity. A bearing whose length was approximately equal to its diameter was found experimentally to be satisfactory for both its load carrying capacity and stability. A bearing clearance of 0.0003 inch for the 1/8 inch shaft was found experimentally to be a good compromise between excessive oil leakage and bearing friction. Less clearance generated more heat than the silver bearing could dissipate, while greater clearance resulted in greater oil leakage. A turbine with this bearing design was successfully run at 13,500 rps for periods up to 1/2 hour without damaging the bearing.

The first successfully operated rotating mirror assembly consisted of a 3/4 inch by 1-3/4 inch by 5/16 inch thick steel mirror supported on both ends by silver sleeve bearings. Oil from an external reservoir was circulated through both bearings at a rate of 0.3 gal/min for lubrication and cooling. A 1/2 inch diameter turbine rotor was pressed on both ends of the mirror shaft between the bearing and rectangular mirror section. A stationary air nozzle plate was located between the rotor and mirror. Air at 50 psig was supplied to the jet nozzle through channels in the assembly body at flow rates up to 50 cfm. Air flow was directed away from the mirror towards the sleeve bearings and through exhaust ports. Oil mist generated during operation by rotation of the mirror shaft was blown away from the mirror by exhaust air. Oil leakage on the mirror still resulted in fouling of camera optics when the mirror was operated after remaining idle for several hours. This mirror assembly is described in greater detail in Exhibit 4.

While bearing designs were being evaluated, Laboratory engineers carried out a survey of commercially available steels in order to find the steel with the highest tensile strength. Allegheny Ludlum 609 was chosen for mirrors operated up to 10,000 rps. This steel was one of the strongest tested, having an ultimate strength of 375,000 psi and Rockwell hardness of C-57. In addition, the Allegheny Ludlum 609 could be successfully polished with ordinary optical polishing methods. The poor corrosion resistance of this steel, however, necessitated the vacuum depositing of a thin layer of aluminum followed by a protective layer of silicon monoxide. These coatings on the polished mirror face eliminated corrosion and increased reflectance of the mirror surface.

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[1] Milton C. Shaw, and E. Fred Macks, Analysis and Lubrication of Bearings, McGraw-Hill, 1949.

A typical design problem encountered during development of the first 10,000 rps mirror assembly was that of attaching the rotor to the mirror shaft. It was not possible to machine the rotor blades integrally with the shaft since the process used to polish the mirrors required that the mirror face be the highest point contacting the grinding and polishing surfaces. Several schemes were tried for holding a turbine rotor on the mirror shaft including holding the rotor against a shoulder with a threaded unit, and shrink fitting the rotor on the shaft. The method finally utilized was to press the rotor over a short 1° tapered section of the mirror shaft. The outer diameter of the rotor was held to 0.520 inches or approximately one-half the width of the steel mirror. The rotor was machined from Reynolds Alloy 303 aluminum. When the 2:1 ratio of diameters was held, the speed at which the turbine blades would fly off the rotor was equal to the speed at which the rotor would loosen from the shaft and to the bursting speed of the mirror itself.

Compressed air was used for driving the mirror to speeds up to 7,000 rps. The peripheral velocity of the mirror at this speed was approximately equal to the speed of sound in air. Air was not adequate for spinning the mirror above 7,000 rps. There were two reasons for this difficulty. First, when the peripheral speed of the mirror reached the speed of sound, standing shock waves were created and the power required to drive the mirror increased sharply. Second, because the air exit velocity for the present nozzle design was limited to the speed of sound of the driving gas used and because the maximum efficiency of a single-rotor turbine occurs when the rotor peripheral velocity equals one-half the velocity of the driving medium, air became less effective as the rotor peripheral speed exceeded one-half the speed of sound. The turbine could be driven to higher speeds using a light gas such as helium in which the speed of sound was several times that of air. The speed limitation on the rotating mirror became that of the mechanical strength of the mirror and rotor when helium was used as the driving medium. Typical operating curves for this 10,000 rps rotating mirror assembly are included in Exhibit 4.

Buck Instrument Company Developments, 1954-1962

In 1954, Mr. Buck left the Los Alamos Scientific Laboratory, organized the Buck Instrument Company in Boulder, Colorado, and began manufacturing mirror assemblies. In 1955, the company had five employees, including three machinists and two technicians who assembled and tested mirror assemblies. Mr. Buck held patents on several important features of the rotating mirror assembly that he had developed after having left Los Alamos. As of 1958, several significant changes were made in the design of the mirror assembly. The first change was made to help minimize the vibrations of the mirror which had occurred in the Los Alamos models. Whereas the silver sleeve bearings in the early models were rigidly retained in the body of the assembly, the new design incorporated sleeve bearings which were free to move radially, several thousandths of an inch. The motion was damped by a cushion of oil surrounding the bearing. Axial bearing movement was held to several ten thousandths by a bearing flange which was "sandwiched" between the bearing retainer and the bearing holder.

The retainer also maintained compression in the "O" ring between the bearing and holder. The "O" ring served to help keep oil out of the turbine area. This redesigned 10,000 rps mirror assembly is described in greater detail in Exhibit 5.

In the new design, oil was supplied to the bearings from an oil reservoir located at one end of the mirror assembly. A 0.02 inch diameter passage was drilled in the end of the mirror shaft and served as a centrifugal pump. Oil was pumped from the reservoir through the adjacent bearing. A passage in the assembly body led to the opposite bearing, and a similar passage returned oil to the reservoir. The pump and oil reservoir eliminated the external oil connections.

The redesigned mirror assembly used two turbine rotors, each one located between the mirror and sleeve bearing on each end of the shaft. The flow of compressed helium or compressed air through the rotor and past the sleeve bearings at both ends of the mirror improved the oil mist problem when the mirror was operating; however, an oil film would still form on the mirror shaft and rotor during idle periods. The oil mist which resulted when the mirror was used again still remained an unsolved problem.

The new assembly used a magnetic pickup whose output provided a synchronizing signal for initiating an event to be photographed. The end of the mirror shaft opposite the oil reservoir protruded beyond the sleeve bearing and was magnetized with poles arranged radially across the shaft. A soft iron core pickup and copper winding enclosed the end of the mirror shaft. When the mirror rotated, the magnetic field turning relative to the pickup created a sinosoidal signal with frequency equal to the speed of the mirror. The output varied between plus and minus 10 volts. The phase of the signal relative to mirror position varied with speed of operation of the mirror. Due to the frequency variation of the pickup impedance, provision was made for rotation of the pickup relative to the assembly body by means of a movable, calibrated end plate. The pickup feature allowed for phase adjustment of the synchronization signal to accommodate, for example, time delays between the signal and initiation of the event. The magnetic pickup is described in greater detail in Exhibit 5.

During the testing of a prototype assembly of the new design, it was discovered that the turbine would deviate from the expected pressure/speed curve for the driving medium being used during the test. The deviation was caused, in Mr. Buck's opinion, by resonant vibrations in the mirror and bearing assembly. He felt this opinion was supported by the vibrations in the gas feed line felt by the operating technician during trial runs. The deviation from the speed curve occurred at approximately 7,200 rps. A speed curve representing this variation is described in greater detail in Exhibit 6.

Mr. Buck discovered experimentally that the speed curve deviation could be shifted to a considerably higher frequency above the desired operating speed of 10,000 rps by varying the weight of the sleeve bearings. The experimentation led to the design of the two sleeve bearings, one of which was approximately twice as heavy as the other. Vibrations were not experienced with the heavy bearing at one end of the mirror and a light bearing at the other end.

Mr. Buck commented that in spite of the improvements made to the original design, the problem of oil contamination of the camera optics remained the most significant problem of the mirror assembly operation. In 1961, he said, "Even though we have the best product of this type on the market, our customers get used to having this photographic capability, and they ask if we can eliminate the oil mist problem."

<u>Radiation Products Company Developments, 1962 - Present</u>

In 1962, the Buck Instrument Company moved its operations to Santa Clara, California, and changed its name to Radiation Products Company after affiliating with Technical Operations, Inc., of Burlington, Massachusetts. Shortly after the 1962 relocation of the company, two major design changes were made to improve the operation of the mirror assembly. First, to reduce the cost of operating the assembly, Mr. Buck decided to operate the mirror in a vacuum. Randy Sherman, Manager of the Turbine Department, noted that the 120 psi helium at 60 ft^3/min required to operate the turbine cost approximately $15/minute. Operating the assembly with the turning in a vacuum reduced this cost to approximately $4/minute.

Randy felt that the helium cost reduction was an important selling point. He said, "Consider the case of a munitions manufacturer who desires to use the high speed camera as a quality control tool. If every thousandth round were test fired and photographed, the camera would be operated for 30 seconds every 15 minutes, 8 hours a day. A 75% cost reduction for helium consumption at this rate is a significant feature of the new design."

The second design change was made in an attempt to cure the oil mist problem. Mr. Buck decided that a good way to eliminate the mist was to substitute ball bearins for the silver sleeve bearings. Ball bearings did not require a constant flow of lubricating oil for cooling. Experiments with ball bearings at the Los Alamos Scientific Laboratory had used ball bearings mounted directly on the mirror shafts. The new Radiation Products design used a planetary arrangement of three ball bearings spaced at 120° intervals around one end of the mirror shaft. A second ball bearing arrangement could not be used on the other end, adjacent to the turbine rotor, since Radiation Products engineers did not know how they would seal ball bearings to keep the driving gas out of the mirror cavity. Consequently, a silver sleeve bearing was used at the rotor end of the mirror shaft. The design of the 10,000 rps evacuated mirror assembly is described in greater detail in Exhibit 7.

Installation of the ball bearings helped reduce the problem of oil fouling. The ball bearings were cleaned with acetone and dried with filtered air prior to lubrication. A small quantity of Socony-Vacuum Type DTE light oil was used to lubricate the bearings. Excess oil was blown off the bearings just prior to installation in the assembly. In spite of these precautions, however, oil was still seeping onto the mirror shaft during idle periods between camera operation. In addition, when the vacuum and driving gas were shut off to stop the turbine, oil would begin to leak into the cavity since there was no counter gas flow to keep the oil out of the cavity. This contribution to the contamination was eliminated by continuing to apply the vacuum while the mirror came to a stop. The idle seepage remained, however.

In August, 1963, shortly after the bearing design was changed, testing was initiated on the first three redesigned assemblies. Dwight Smith, a laboratory technician, noted that the first unit was assembled and tested up to 11,000 rps, with no indications of mechanical problems. Several difficulties did arise, however, during the tests of the second unit. During the first series of tests, Dwight burned out 12 silver bearings. The failures were indicated by rough, noisy running of the turbine. Dwight said, "In several cases, it appeared from looking at the bearings that the silver surface of the bore had actually become fluid from the generated heat." The mirror had been operated at speeds up to 9,200 rps for all twelve tests.

Dwight installed a second mirror and another silver sleeve bearing. A sleeve bearing was prepared for assembly by burnishing the slightly undersized bearing bore with 1° tapered steel rod until the bearing would lightly slide on the mirror shaft. Dwight said, "The clearance is adjusted only by feel. I burnish the bore until the bearing just drops on the mirror shaft. If it's sort of tight, I try to wear it in during operation of the mirror." Measurement with a calibrated tapered rod indicated that the bearing bore was typically 0.0001 inch larger than the shaft. During this run-in period, the driving medium pressure was regulated in successive 10 psi steps, and the turbine was operated 5 to 10 seconds at one pressure setting, allowed to coast to a stop, then operated at the next setting. Dwight said, "I can tell if the bearing is tight, because the turbine slows down rapidly."

When Dwight installed the second mirror, he increased the axial play between the thrust washer and the silver sleeve bearing. He observed during the subsequent test run that the pressure/speed curve "didn't look quite right". After the test, he disassembled the turbine and found that the thrust washer had cut deeply into the bearing. Dwight felt that the cutting was probably due to either an unparallel washer, or a severe axial vibration. He had observed axial vibrations in low speed tests on the first unit through the back of the assembly operated with the hand adjustment removed. He said, "The axial vibrations were very noticeable at about 1000 rps. At higher speeds, the turbine mirror seemed to seek one end or the other."

Dwight installed a new bearing and thrust washer, using the same mirror. He reduced the axial play to approximately 0.005 inches. During the first test run on the new bearing, Dwight noticed gas bubbles in the return stream which he could observe through the lucite reservoir window. He continued the test run and increased the speed of the mirror from 9,200 rps to 9,300 rps. After 30 to 40 seconds of operation at the higher speed, the mirror shaft adjacent to the sleeve bearing snapped off at the junction with the mirror.

Double Planetary Bearing Suspended Mirror

During operational tests of the assembly with the evacuated mirror cavity, Bob Herbold completed work on a mechanical seal which allowed use of two sets of ball bearings in the mirror assembly. Details of the seal operation have been withheld at the request of Radiation Products Company. The first mirror assembly to use the new design was made from a modified assembly of the previous evacuated turbine design. Sketches for the modification were made by Mr. D. Hanson, Radiation Products draftsman, after several discussions with Bob Herbold and Dwight Smith. The end of the mirror previously suspended by the sleeve bearing was now supported by a planetary ball bearing arrangement almost identical to the first planetary design. The assembly body was modified to accept three new bearings mounted on a bearing holder with bearing shafts as before. A dry seal mounting plate was installed between the new bearing assembly and the turbine rotor. Driving gas was ducted to the turbine nozzles and rotor through a new nozzle holder. The planetary bearing suspended rotating mirror assembly is described in greater detail in Exhibit 8.

Mirror Failures

The first test of the double ball bearing assembly was performed on July 7, 1964. Dwight said, "During that first run, the assembly made more noise than usual. It seemed that the mirror was vibrating badly or going out of balance. The resonance occurred at 7,085 rps." Dwight disassembled the turbine and checked the balance of the mirror on a tester.

The mirror could be balanced by lapping during manufacture to a balance of approximately 2.5×10^{-5} inch-ounces. Details of the balancing operation were proprietary secrets of Radiation Products Company. Dwight determined that the mirror was out of balance and that the bearing post "O" ring seats were worn on the edge toward the mirror shaft. He said, "I think that the wear results from contact between the bearing inner races and the 'O' ring seats. Apparently the shafts are bouncing between the bearings in a 3-point fashion."

Dwight installed a new mirror and bearing parts and began a new test sequence. During the first test, he could feel vibrations in the air supply line close to the turbine body. The vibrations occurred when the mirror was running at approximately 7200 rps. After this test run, Mr. Buck, Randy Sherman, and Dwight Smith all agreed that "O" ring tension between the bearings and maintaining posts should be increased. Consequently, a cam arrangment for each post was designed and installed in the

modified assembly. The cam adjustment allowed for 0.014 inches of radial movement of the bearing post toward the mirror shaft axis. Dwight said, "Even with the adjustable post, we couldn't get around the resonance problem completely. The assembly would still deviate from the expected speed curve, although the point at which this deviation occurred could be shifted by 200 rps or so."

In the next attempt to eliminate the speed control problem, the design of the planetary bearing arrangement of an experimental assembly was changed to include two different sizes of bearings. Three bearings with O.D. of 0.375 inches were used on one end of the shaft and three bearings with O.D. of 0.738 on the other end. The purpose of this arrangement was to determine the effect of different ball speeds on the mirror assembly performance. During tests of this assembly, Dwight noted several points along the pressure speed curve where trouble occurred. At 20 psi, 20 ft^3/min, for example, the turbine was turning at 3,120 rps, and Dwight heard a low pitched rumbling sound from the assembly. He then dropped the driving pressure and allowed the mirror to coast to a stop. With pressure set at 30 psi, 30 ft^3/min, the turbine ran at 3,930 rps, and Dwight noticed a deep cycling type noise.

Dwight gradually increased the air pressure and flow rate in successive steps up to 75 psi, 70 ft^3/min, and the mirror reached 8900 rps. At this speed, he felt heavy vibrations in the air line. As the vibrations continued, the speed dropped to 3400 rps without change in pressure and flow rate readings. Dwight immediately shut off the air supply and allowed the turbine to coast to a stop. He disassembled the mirror and placed an optical flat on the mirror surface. Any distortion of a flat surface was observable as interference lines on the mirror face under monochromatic light. Dwight did not detect any mirror bending with the optical flat or any unbalance with the balance detector. After checking the bearings, he reassembled the turbine with the same parts. During subsequent tests, Dwight detected vibrations at 7160 rps. He decided to discard the mirror.

Randy Sherman noted that it was difficult to isolate problems causing the mirror failures. He said, "I don't think that there is a single contributing factor that causes the speed curve deviations and shattered mirror, but rather a chain of occurrences. Ideally, what we would like to do is eliminate one variable at a time. When this happens and everything runs okay, then we will have found the variable causing the trouble."

In order to eliminate the effect of mirror unbalance, a "mirror" consisting entirely of a cylindrical section was constructed. The normally 3/4 inch x 1-1/2 inch x 1/4 inch thick mirror section was reduced to a 1/4 inch diameter cylinder. Other typical mirror dimensions and tolerances were maintained. Randy said, "We have achieved speeds up to 20,000 rps with test assemblies using this type of cylindrical mirror. I think that mirror unbalance that cannot be corrected by removing material from one of the mirror surfaces is the primary cause of the failures."

In spite of successful operation of cylindrical mirror assemblies, difficulties with rectangular shaped mirrors persisted. Randy Sherman reported that several variations in the design of the bearing mounting were used in an attempt to eliminate what he felt was "bounce" of the mirror shaft. He said, "We tried mounting the bearings rigidly to the support plates and found that the mirror shafts broke off immediately at low speeds around 1500 rps. Since we can't balance the mirrors perfectly at speeds near or above 1500 rps, the mirror wants to rotate about its mass center, not its geometric center. Therefore, we can't rigidly constrain the bearings or support plate -- you have to let it go where it wants to go."

Dwight ran several more tests with all steel mirrors. During one run, the turbine began to deviate from the pressure/speed curve at approximately 7160 rps. He said, "I tried to over-pressure the turbine by 10 pounds of over-pressure, but it remained at that speed." After 15 seconds of operation at 10 pounds of over-pressure, the mirror exploded inside the test chamber. Randy said, "When a mirror explodes, it is probably because of some defect in the mirror material. We are presently using ultra-sonic and X-ray testing of the mirror bar stock we use in making mirrors. With ultra-sonic, we can detect voids down to 1/32".

Beryllium Mirrors

The latest attempt by Radiation Products to eliminate speed control and vibration difficulties centered on the use of beryllium as a mirror material. In August, 1964, Randy Sherman said, "The high tensile strength to weight ratio and high Young's modulus for beryllium means that it can be used at higher speeds without distortion than steel. Distortion is caused by the outward pull of outer portions of the mirror on the center section. The low Poison's ratio of beryllium results in less distortion." The beryllium mirrors were machined from bar stock supplied by the Brush Beryllium Company.

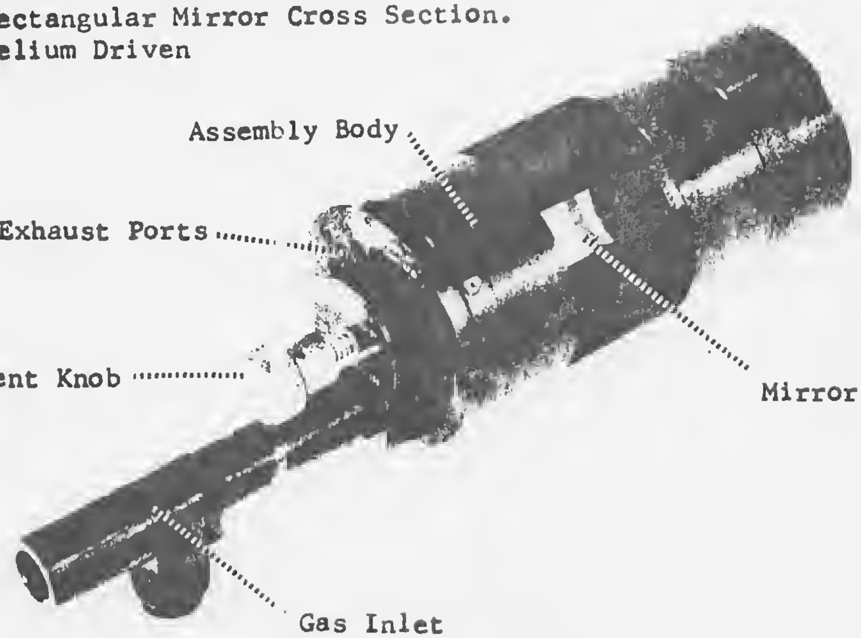
Steel bearing end caps were pressed over tapered ends of the mirror section to provide a hard wearing surface in contact with the bearing outer races. The complete mirror assembly was ground, balanced, and optically polished like the standard rectangular steel mirrors. Randy said, "I think that the mirror failures that occur are caused by bending of the mirror. The bending is caused by mirror unbalance that cannot be corrected by removing material from the mirror surfaces. Material must be removed from a mirror in a way that won't affect camera optics or cause unbalanced movements on the mirror. Since it is not always possible to remove material 180° opposed to a material void, for example, it is impossible to avoid unbalanced moments on the mirror. Once the mirror starts distorting, the distortion contributes to the unbalance, causing more distortion and so on, until the mirror shatters or the shafts break off. Since we can't balance the mirrors at speeds near the speed at which they fail, we must discard four of every ten mirrors we make. This gets very expensive since each mirror costs approximately $420 to make. We manufacture about 100 successful mirrors of the type used in high speed photographic cameras per year."

Mr. Buck said, "If the deviation from the speed curves is caused by resonant vibrations in the center section of the mirror, the beryllium will help move the resonant frequency above the operating range that we are interested in because of its high strength to weight ratio. If the vibration occurs because of the small size of the bearing end shafts, the beryllium may help because these shafts have less load to support with the lighter beryllium mirror. The problem wasn't so severe until we changed our bearing designs in order to improve overall quality of operation of the assembly. With the present bearing and mirror design, the mirror and bearing assembly seems to have a resonant frequency at approximately 7200 rps. Frequently, the turbine will run to that speed with 50 psig air at 50 cfm and will then absorb the energy of 100 psig at 80 cfm with no increase in rotational velocity. Sometimes it is possible to force enough energy into the turbine system to drive the mirror through the resonant point, but then there is so much energy going into the system that the turbine will accelerate faster than you can control it and explode from overspeeding. We would like to operate in this speed range, but we've got to solve this resonance problem to do it."

Exhibit 1. Turbine Department Products.

Model #189-07 Rotating Mirror Assembly

Specifications: 10,000 rps Max. Speed.
0.680 x 1.000 Mirror Face,
Rectangular Mirror Cross Section.
Helium Driven



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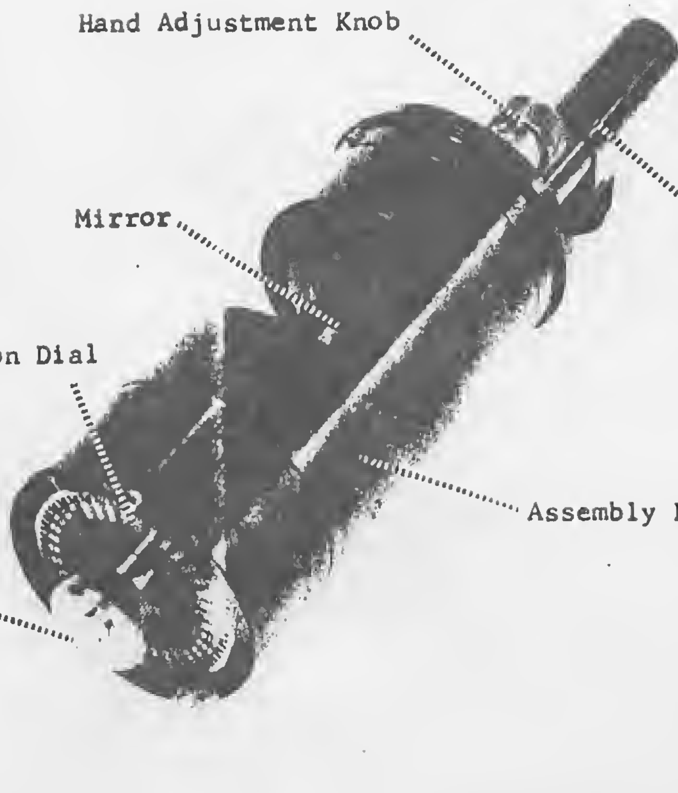


Courtesy of Radiation Products Company

Exhibit 2. Employee Resumes

EMPLOYEE		RESUME
Randy Sherman	1954-1956	Technician, University of Colorado High Altitude Observatory.
	1956-1962	Technician, Buck Instrument Company Boulder, Colorado.
	1962-present	Manager, Turbine Department Radiation Products Company Santa Clara, California
Bob Herbold	1930-1935	Consultant, Diversified Patents Co.
	1935-1964	President, Herbold Product Laboratories
	1941-1945	Engineer, Remington Arms Company
	1955-1958	Consultant, Continental Foods, Inc.
	1958-1963	Consultant, Cado Corporation
	1962-1963	Consultant, Jerome Labs, Inc.
	1963-present	Mechanical Engineer, Turbine Department Radiation Products Company Santa Clara, California
Willard E. Buck	1947-1952	Mechanical Engineer, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
	1952-1962	President, Buck Instrument Company Boulder, Colorado
	1962-present	Consultant, Turbine Department Radiation Products Company Santa Clara, California
Dwight Smith	1953-1954	Mechanic, Arnold Motor Company
	1956-1960	Technician, Iowa Electric Light & Power
	1960-1962	Research Technician, Buck Instrument Co. Boulder, Colorado
	1962-present	Assistant Manager, Turbine Department Radiation Products Company Santa Clara, California
Derald Hanson	1955-1958 1961-1962	Draftsman, Allis Chalmers Manufacturing Company, Cedar Rapids, Iowa
	1962-present	Draftsman, Designer, Turbine Department Radiation Products Company Santa Clara, California

Exhibit 3. Camera Operation.

Beckman & Whitley Inc.
San Carlos, California

I. GENERAL DESCRIPTION

The Model 189 Framing Camera is a synchronized rotating mirror camera utilizing the "Miller" principle for shuttering and image transmission. The objective lens and field lens combined place an image precisely upon the face of the rotating mirror. As the mirror rotates, illumination is routed successively to adjacent pairs of relay lenses; each relay lens pair receives illumination only at the position of the mirror in which the image appears to the relay lens position to be stationary and perpendicular to the relay lens optical axis.

Highly efficient shuttering is accomplished by admitting the image forming beam from the objective lens through a diamond-shaped entrance stop near the objective lens. A field lens close to the rotating mirror and on the same optical axis as the objective lens causes the entrance stop, routed exactly along the main image forming system axis, to be imaged at a point between the relay lens pairs. By placing a mask with diamond-shaped apertures between the relay lenses, the sharply formed diamond-shaped image transmitting beam is scanned over the openings in the exit stop mask, providing highly efficient between-the-lens shuttering.

The twenty-five pairs of relay lenses which produce static images on a stationary film are, in effect, twenty-five separate cameras, shuttered successively by action of the rotating mirror.

Focusing is accomplished by retractable focus device examination of the image on the rotating mirror through one of the relay lens pairs.

The basic 189 Camera includes a 5000 RPS (Revolutions Per Second) turbine driven mirror; however, the 10,000 or 17,000 RPS turbine driven mirrors can be interchangeably used, thus permitting higher framing rates (up to 4,000,000 frames per second).

Film fogging is prevented by a mechanical shutter mounted on the objective lens tube housing. A "Time-Instantaneous" switch and

I. <u>GENERAL DESCRIPTION</u> (CONTINUED)

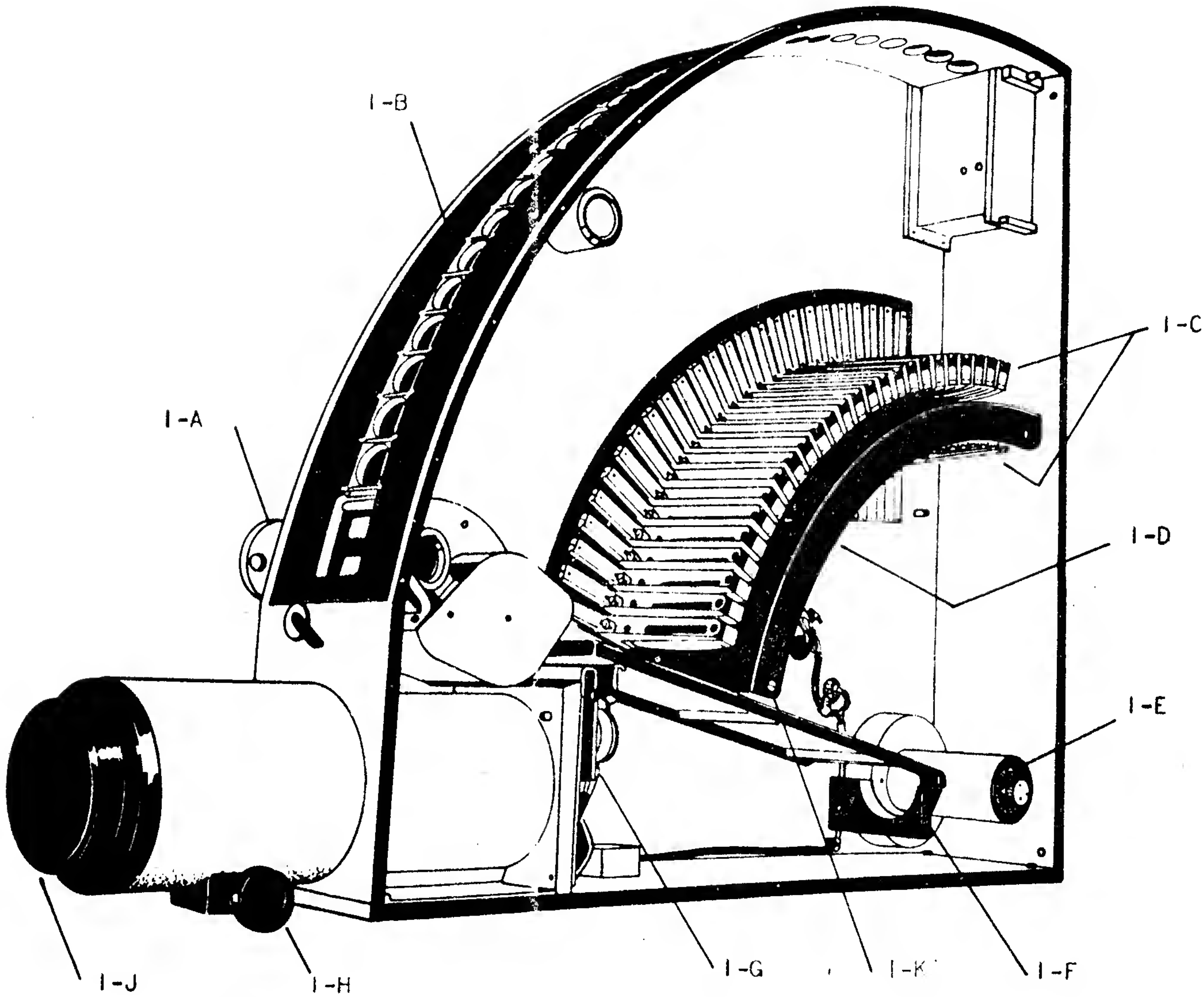
A "SHUTTER OPEN" PILOT LIGHT ARE PROVIDED TO CONTROL AND MONITOR SHUTTER OPERATION. THE FILM MAGAZINE HOLDS 100 FEET OF 35 MM DAYLIGHT-LOADING PERFORATED FILM. A STANDARD 35 MM FILM CARTRIDGE OPERATED BY A HAND CRANK, PROVIDES FILM TAKE-UP AND DAYLIGHT UNLOADING. A MECHANICAL COUNTER MEASURES FILM FOOTAGE USED.

THE BECKMAN & WHITLEY MODEL 100 CAMERA CONTROL, THE TYPE 30 REMOTE CONTROL, CONTAINING POWER SUPPLY, SYNCHRONIZATION UNIT, SWITCHING UNIT AND AIR REGULATOR, AND THE MODEL 329 HIGH VOLTAGE PULSE UNIT IS RECOMMENDED TO BE USED WITH THE MODEL 189A TO FUNCTION AS AN INTEGRATED SYSTEM.

CAMERA REWRITE CAN BE PREVENTED THROUGH USE OF THE BECKMAN & WHITLEY MODEL 234 BLAST SHUTTER WHICH IS TRIGGERED BY THE BECKMAN & WHITLEY MODEL 329-4 HIGH VOLTAGE PULSE UNIT.

ENG. 9103-004
1 JULY '63

Beckman & Whitley INC.
SAN CARLOS, CALIFORNIA



I-A FOOTAGE INDICATOR
I-B FILM TRACK
I-C MATCHED RELAY LENSES
I-D DIAMOND STOP
I-E TURBINE

I-F FIELD LENS
I-G CAPPING SHUTTER ASSY.
I-H FOCUSING KNOB
I-J OBJECTIVE LENS ASSY.
I-K SCREW

INTERNAL VIEW
OF THE
MODEL C189 SYNCHRONOUS FRAMING CAMERA

Exhibit 3. Camera Operation.

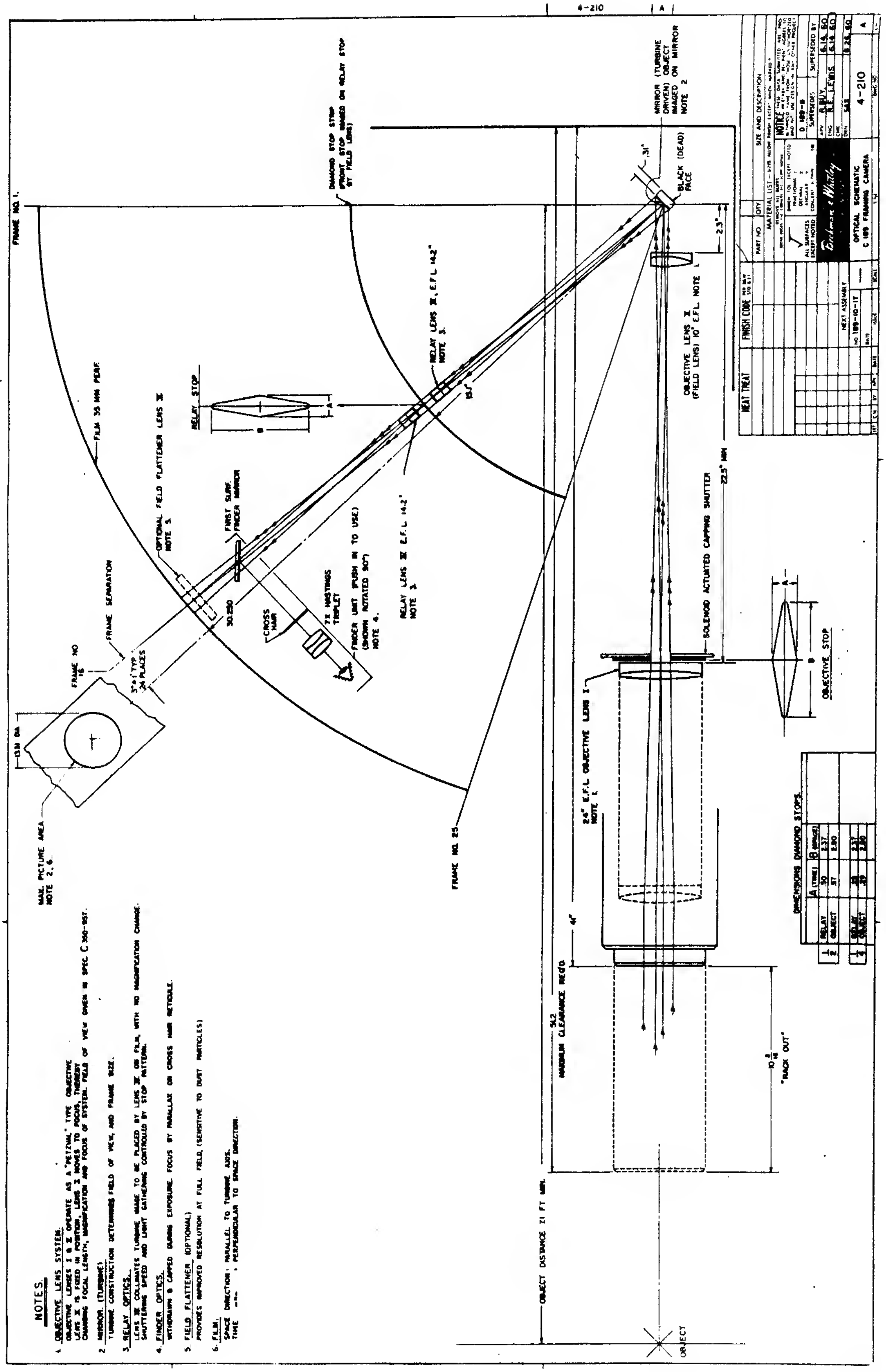
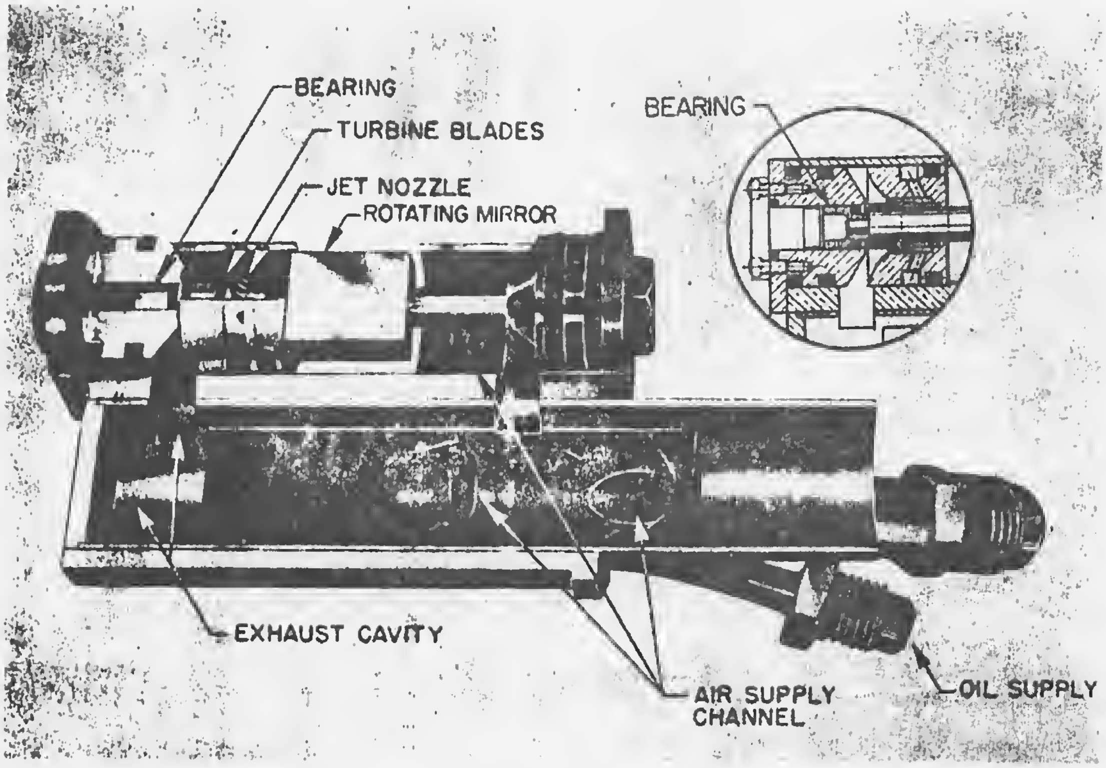
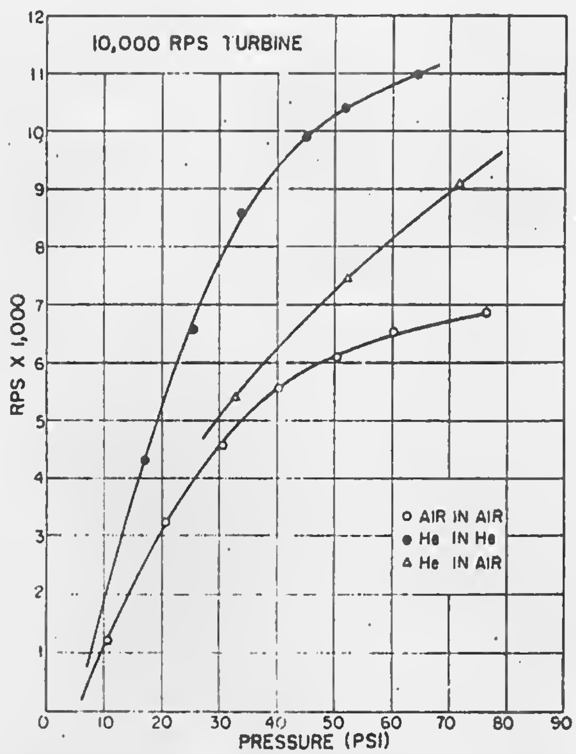


Exhibit 4. Los Alamos 10,000 rps Rotating Mirror Assembly

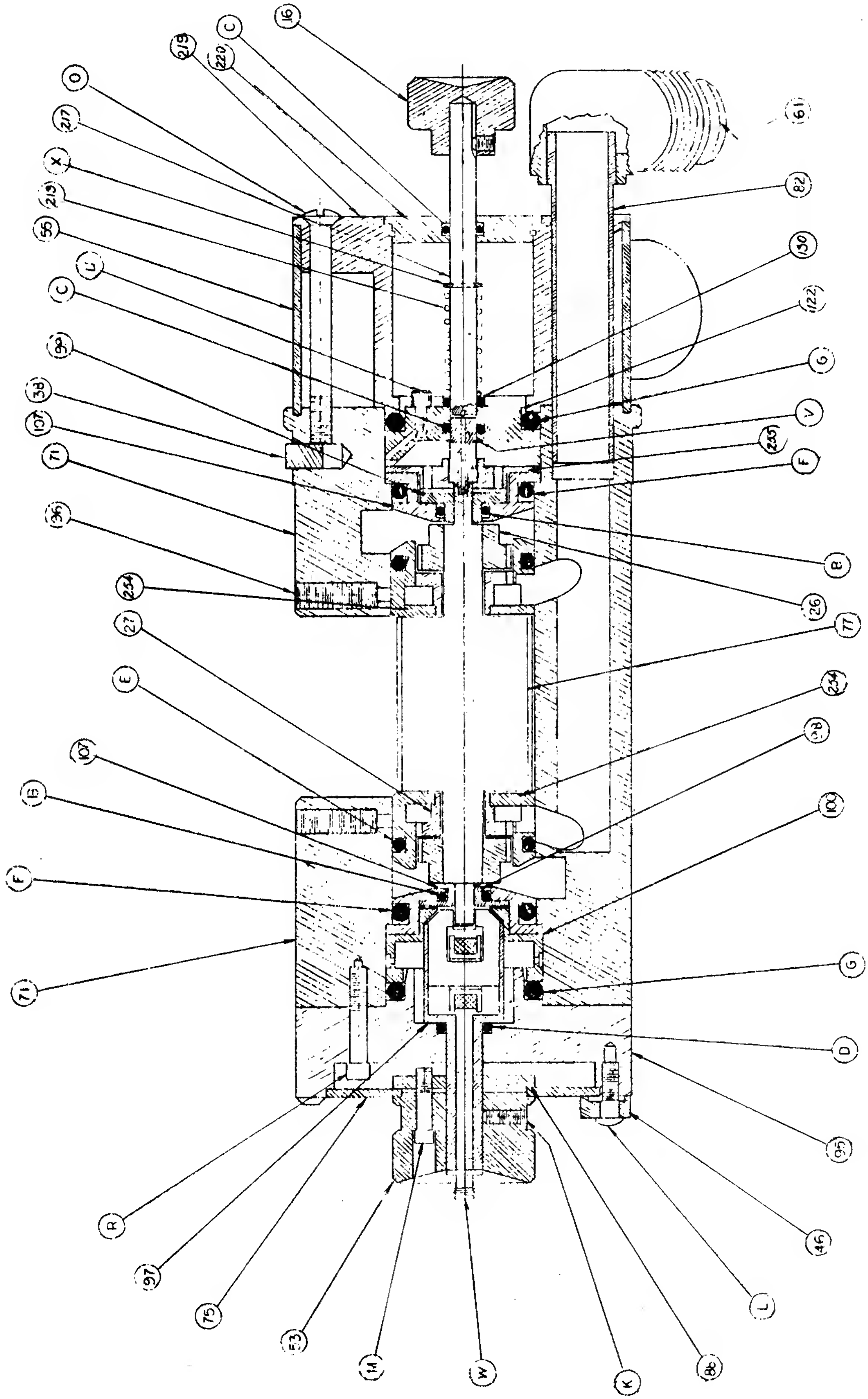


Cutaway View, Rotating Mirror Assembly



Typical Pressure/Speed Curve, 10,000 rps Mirror

Exhibit 5. Buck Instrument Company 10,000 rps Mirror Assembly, Model # 189-02.



Courtesy of Radiation Products Company

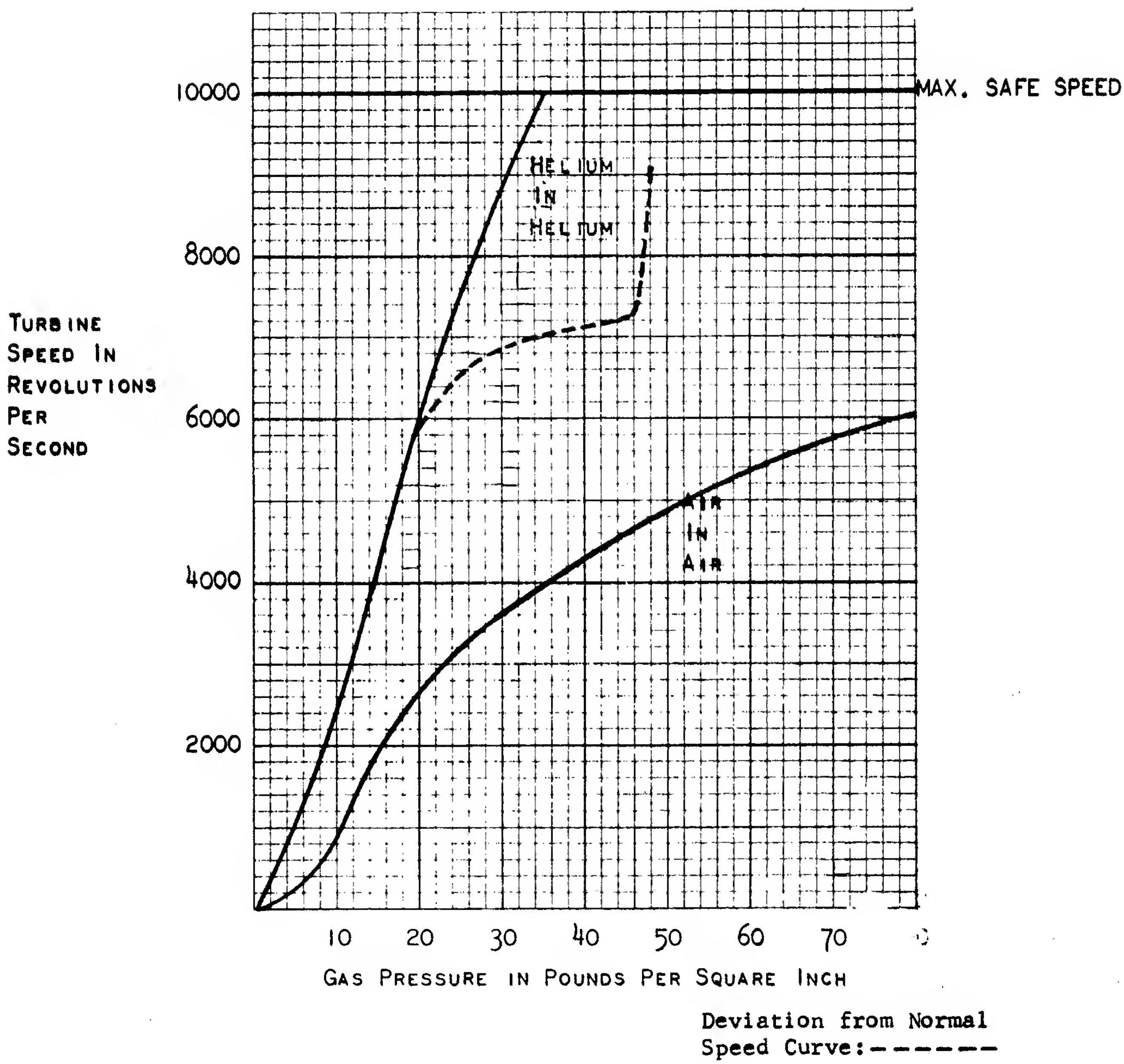
Exhibit 5. Buck Instrument Company 10,000 rps Mirror Assembly
Model #189-02.

ASSEMBLY DRAWING PARTS LIST

Reqd.	Part No.*	Description	Reqd	Part No.	Description
1	B-100-16	Adjustment Knob	1	B-10-213	Spring
2	B-200-26	Turbine Rotor	1	B-10-214	Relief Valve
2	B-200-27	Turbine Vane	1	B-20-217	Mirror Adj. Shft.
1	B-100-38	Aligning Stud	1	B-40-219	Oil Reservoir
1	B-100-46	Dial Hold Down	1	B-10-220	Window
1	B-100-53	Synch Knob	1	B-10-221	Filler Plug
1	B-200-55	Oil Res. Shield	2	B-20-254	Nozzle Housing
1	B-200-61	Air Inlet Elbow	1	B-20-255	Bear. Retainer
1	B-400-71	Body	3	A	"O" Ring Size 1/4
1	B-100-75	Dial Index	1	B	" " " 1
1	B-300-77	Mirror	3	C	" " " 3
1	B-100-79	Check Valve Seat	3	D	" " " 5
1	B-100-80	Check Valve	2	E	" " " 14
1	B-100-82	Air Inlet Pipe	2	F	" " " 15
1	B-100-88	Synch Knob Clamp	2	G	" " " 16
1	B-100-89	Relief Valve	1	I	2-56 x 1/8 Socket HD.
1	B-300-95	Cap Coil End	2	K	4-40 x 1/8 " "
2	B-100-96	Set Screw	1	L	4-40 x 1/4 Button HD.
1	B-300-97	P.U. Coil	3	M	4-40 x 3/8 Socket HD.
1	B-100-98	Bearing	1	N	8-32 x 3/16 Dog Pt.Set
1	B-100-99	Bearing	3	O	8-32 x 1-1/2 Oval HD.
1	B-20-100	Bear. Retainer	3	R	4-40 x 5/8 Socket HD.
2	B-30-107	Turb. Bear. Hold	1	S	6-32 x 1/4 " "
1	B-30-122	Oil Separator	1	U	4-40 x 3/16 Unbrako
1	B-10-130	Washer	1	V	5133-18 S. Ring
			1	W	3103 Microdot
			1	X	X5133-18 S. Ring

*Digits after dash correspond to assembly numbers in Exhibit 5, page 1.

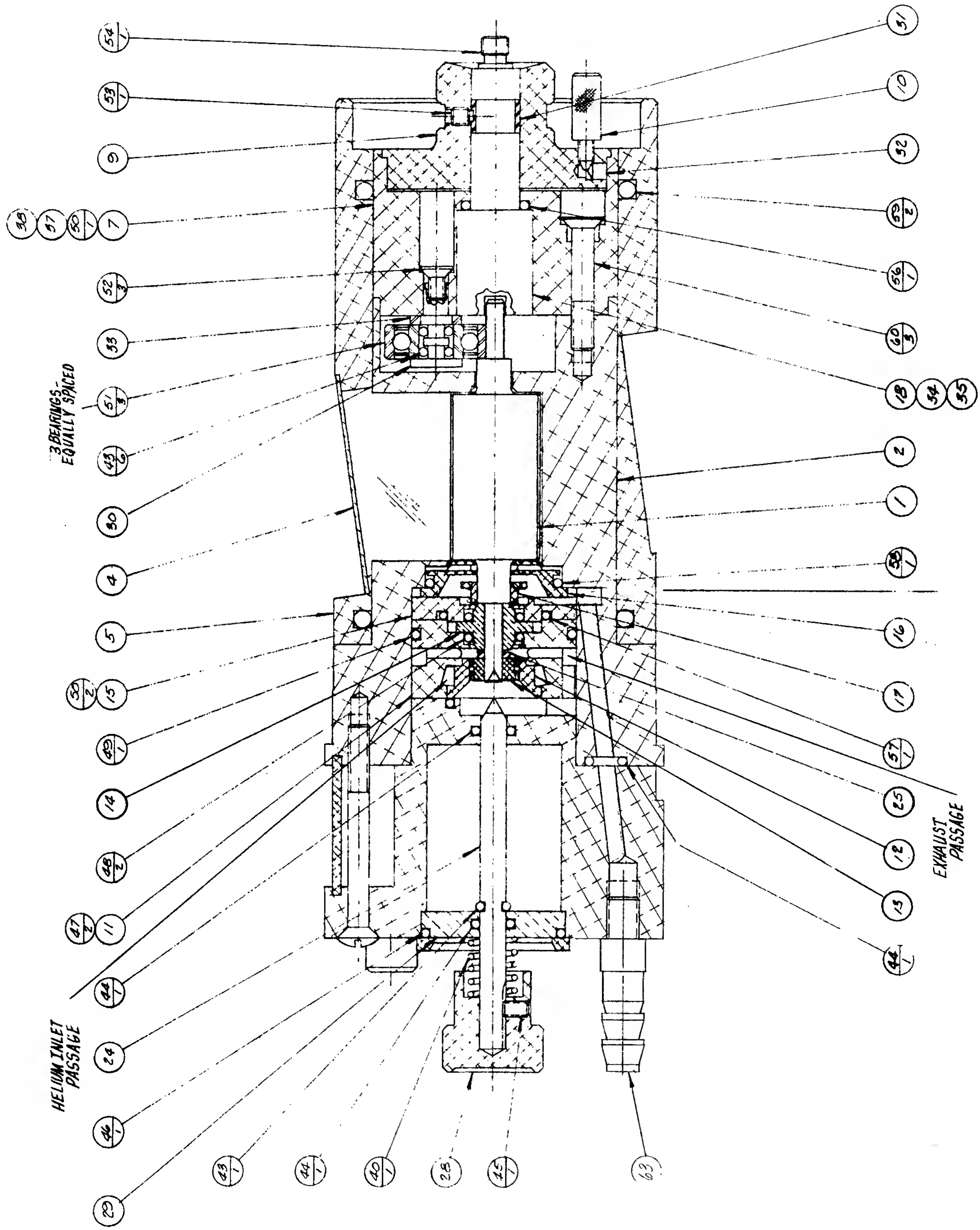
Exhibit 6. Buck Instrument Company 10,000 rps Mirror Assembly, Model #189-02.



TURBINE SPEED vs GAS PRESSURE

Courtesy of Radiation Products Company

Exhibit 7. Radiation Products Company 10,000 rps Mirror Assembly, Model #189-05.



Courtesy of Radiation Products Company

Exhibit 7. Radiation Products Company 10,000 rps Mirror Assembly, Model #189-05.

ITEM	QTY	PART NO.	DESCRIPTION
1	1	20722	MIRROR
2	1	40749	BODY
3	1	40750	RESERVOIR
4	1	20747	WINDOW (PART OF ITEM #5)
5	1	30751	HOUSING, WINDOW
6	1	20752	AIR INLET & POPPET VALVE
7	1	30753	COIL HOLDER & BEARING SUPPORT
8	1	20764	OIL RESERVOIR SHIELD
9	1	20765	SYNCHRONIZER KNOB & DIAL
10	1	10756	KNOB, DIAL LOCK
11	1	30776	NOZZLE & BEARING HOLDER
12	1	10758	NOZZLE INSERT
13	1	10759	WHEEL, TURBINE
14	1	20760	BEARING
15	1	20761	BEARING RETAINER
16	1	10762	BAFFLE
17	1	10763	SLINGER, OIL
18	1	20764	BODY, PICK UP COIL
24	1	20770	SHAFT, MIRROR ADJUSTING
25	1	10771	WASHER, THRUST
26	1	20772	RETAINER, RESERVOIR WINDOW
27	1	10013	OIL FILLER PLUG
28	1	20431	KNOB, MIRROR ADJUSTING
29	1	10773	WINDOW, OIL RESERVOIR
30	1	10634	SHAFT, BEARING
31	1	10774	LOCK RING
32	1	10775	LOCK INSERT
33	3	10650	SPACER, BEARING
34	1	10012	LAMINATION, PICK UP COIL
35	1	10034	WIRE SPOOL
37	1	10829	DISC
38	1	10830	DISC
39	1		"O" RING MRC 8015
40	1		SPRING TO SUIT
42	3		4-40NC BUTTON HD C'SCREW X 1/4
43	7		"O" RING 622701
44	4		"O" RING 622703
45	1		4-40NC SOC. SETSCREW X 1/8
46	1		"O" RING MRC 8021
47	2		"O" RING MRC 8008
48	2		"O" RING 622706
49	1		"O" RING MRC 8024
50	4		ROLL PIN - LENGTH TO SUIT
51	3		BEARING
52	3		4-40NC FLT HD SOC. C'SCREW X 1/4
53	2		8-32NC SOC. S'SCREW X 1/8 (DOG POINT)
54	1		MICRO-DOT CONNECTOR #3105
56	1		"O" RING 622707
57	1		"O" RING MRC 8017
58	1		"O" RING MRC 8020
59	2		"O" RING MRC 8225
60	3		6-32NC FLAT HD C'SCREW X 1
63	1		VACUUM FITTING

Exhibit 7. Radiation Products Company 10,000 rps Mirror Assembly, Model #189-05.

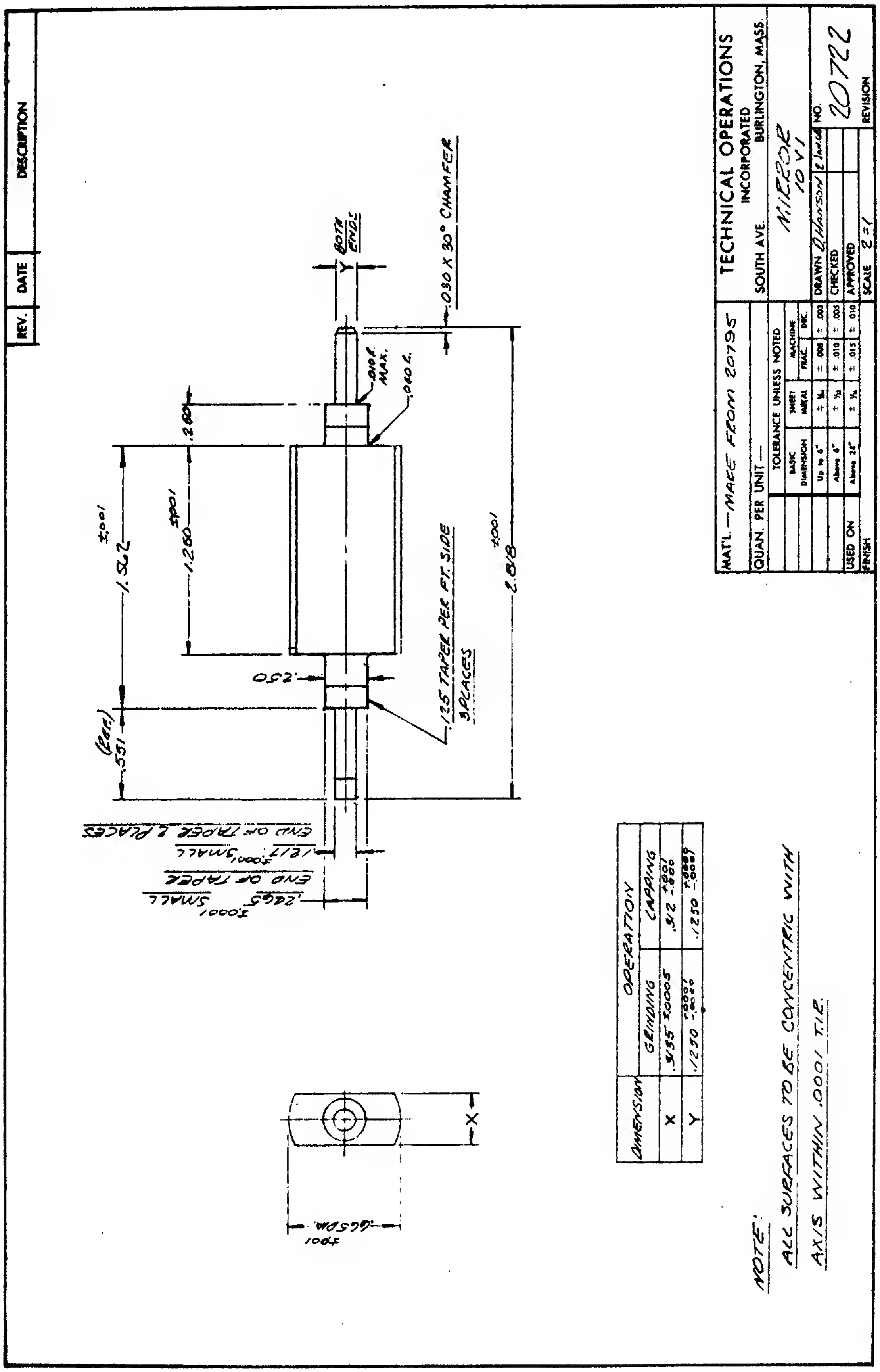
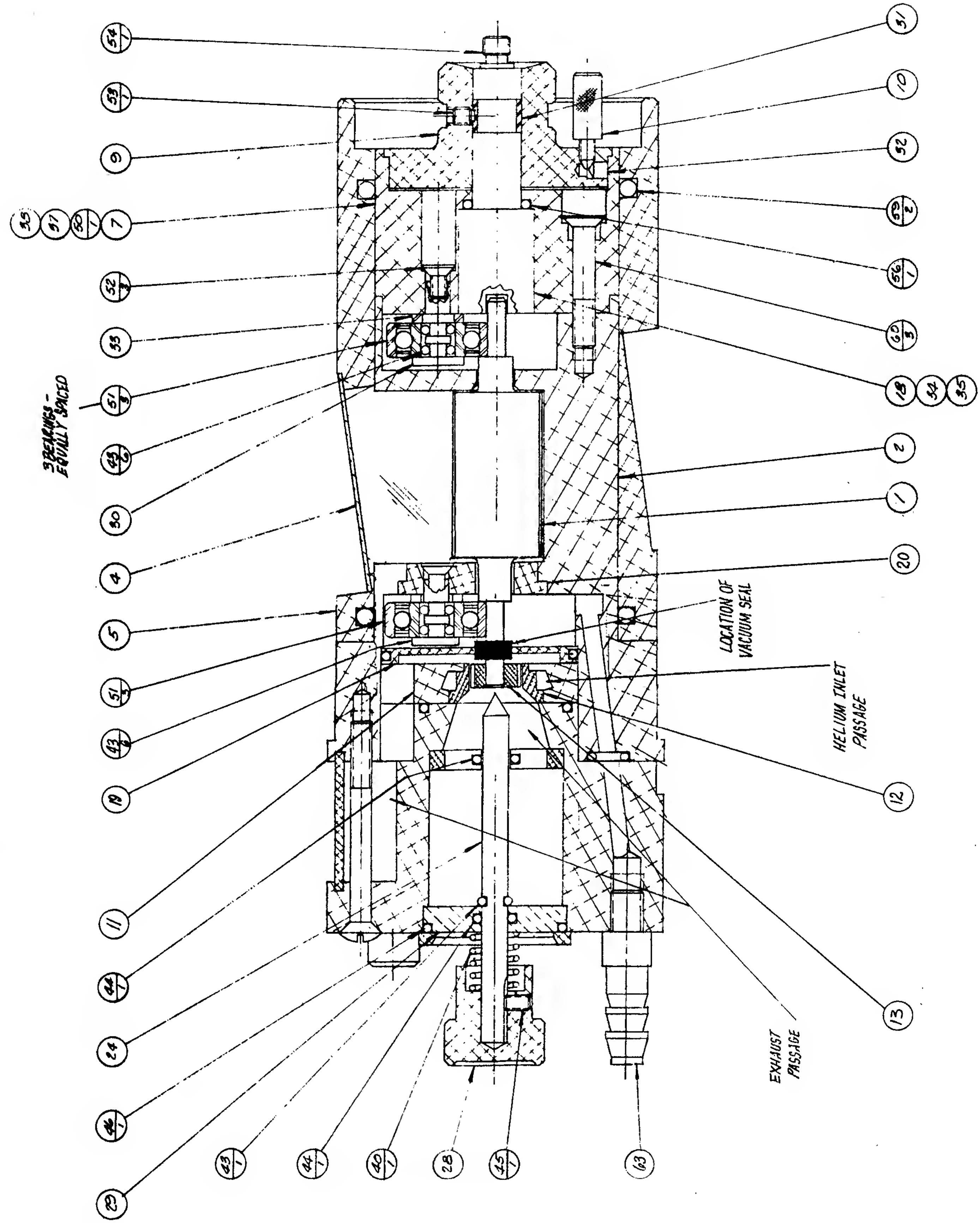


Exhibit 8. Radiation Products Company 10,000 rps Mirror Assembly, Planetary Bearing Suspended Mirror.



Courtesy of Radiation Products Company

Exhibit 8. Radiation Products Company 10,000 rps Mirror Assembly, Planetary Bearing Suspended Mirror.

ITEM	QTY	PART NO.	DESCRIPTION
1	1	20722	MIRROR
2	1	40749	BODY
3	1	40750	RESERVOIR
4	1	20741	WINDOW (PART OF ITEM #5)
5	1	30751	HOUSING, WINDOW
6	1	20752	AIR INLET & POPPET VALVE
7	1	30753	COIL HOLDER & BEARING SUPPORT
8	1	20754	OIL RESERVOIR SHIELD
9	1	20755	SYNCHRONIZER KNOB & DIAL
10	1	10756	KNOB, DIAL LOCK
11	1	30776	NOZZLE HOLDER
12	1	10758	NOZZLE INSERT
13	1	10759	WHEEL, TURBINE
14	1	20760	BEARING
15	1	20761	BEARING RETAINER
16	1	10762	BAFFLE
17	1	10763	SLINGER, OIL
18	1	20764	BODY, PICK UP COIL
19	1		SEAL MOUNTING PLATE
20	1		BEARING MOUNTING PLATE
24	1	20770	SHAFT, MIRROR ADJUSTING
25	1	10771	WASHER, THRUST
26	1	20772	RETAINER, RESERVOIR WINDOW
27	1	10013	OIL FILLER PLUG
28	1	20431	KNOB, MIRROR ADJUSTING
29	1	10773	WINDOW, OIL RESERVOIR
30	1	10634	SHAFT, BEARING
31	1	10774	LOCK RING
32	1	10775	LOCK INSERT
33	3	10650	SPACER, BEARING
34	1	10012	LAMINATION, PICK UP COIL
35	1	10037	WIRE SPOOL
37	1	10329	DISC
38	1	10830	DISC
39	1		"O" RING MRC 8015
40	1		SPRING TO SUIT
42	3		4-40NC BUTTON H'D C'SCREW X 1/4
43	7		"O" RING 622701
44	4		"O" RING 622703
45	1		4-40NC SOC. SETSCREW X 1/4
46	1		"O" RING MRC 8021
47	2		"O" RING MRC 8008
48	2		"O" RING 622706
49	1		"O" RING MRC 8024
50	4		ROLL PIN - LENGTH TO SUIT
51	3		BEARING N.D. Q36UZ07A
52	3		4-40NC FLT H'D SOC. C'SCREW X 1/4
53	2		8-32NC SOC. S'SCREW X 1/4 (DOG POINT)
54	1		MICRO-DOT CONNECTOR #5105
56	1		"O" RING 622707
57	1		"O" RING MRC 8017
58	1		"O" RING MRC 8020
59	2		"O" RING MRC 8025
60	3		6-32NC FLAT H'D C'SCREW X 1
63	1		VACUUM FITTING